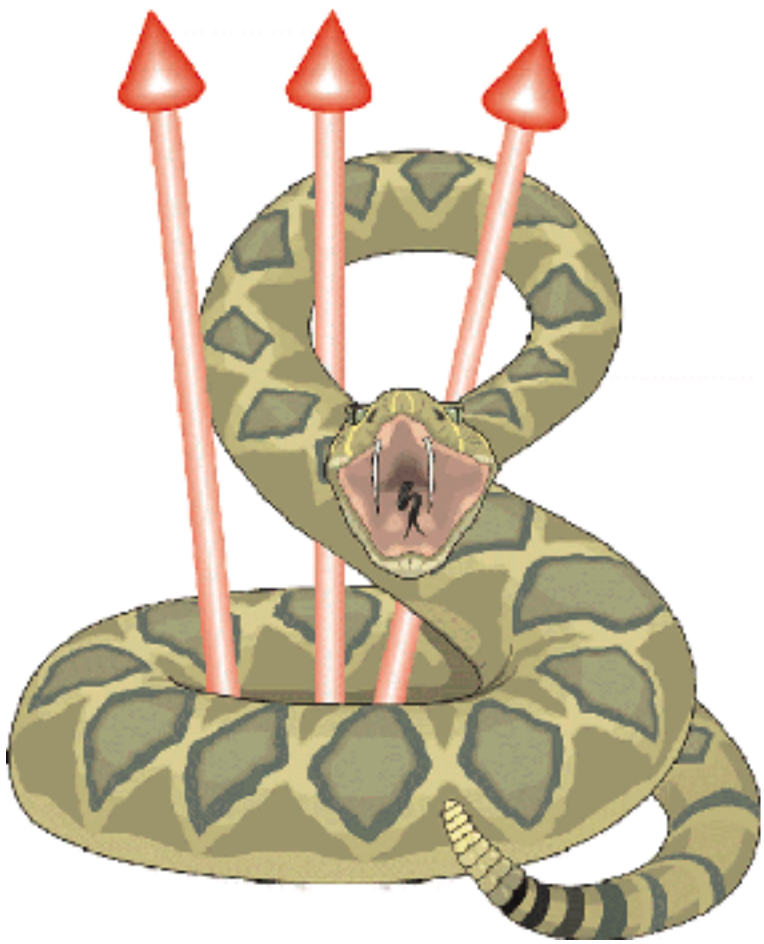
The RHIC SPIN Program

Achievements and Future Opportunities



Writers, for …

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Summary

This document summarizes recent achievements of the RHIC spin program and their impact on the theoretical understanding of the helicity structure of the nucleon and transverse spin phenomena. Open questions are identified and a suite of future measurements with polarized beams at RHIC is laid out to address them. Machine and detector requirements and upgrades are briefly discussed.

The Helicity Structure of the Proton

Helicity parton density functions (PDFs) carry vital information on the extent to which quarks and gluons with a given momentum fraction x tend to have their spins aligned with the spin direction of a nucleon in a helicity eigenstate. The corresponding integrals over all x relate to one of the most fundamental, but not yet satisfactorily answered questions in hadronic physics: how is the spin of the proton distributed among its constituents? The most precise knowledge about helicity PDFs, along with estimates of their uncertainties, is gathered from comprehensive global QCD analyses of available spin-dependent data. Such fits show that while the quark spin contribution is ~30% of the proton spin, the gluon contribution has remained uncertain.

The polarized gluon distribution Δg

Longitudinally polarized proton-proton collisions are currently the best source of information on the elusive gluon helicity PDF, Δg, due to the dominance of gluon induced hard scattering processes. At RHIC, PHENIX and STAR have measured the double helicity asymmetry, A_{LL}, of neutral pions and jets, respectively, at mid rapidity for $\sqrt{s}=200\ \mathrm{GeV}$ in 2005 and 2006, respectively [1,2]. These data were included in the DSSV global analysis [3], and significantly constrained Δg(x) in the region $0.05 < x < 0.2$, finding a result for the corresponding integral consistent with zero, $\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.005^{+0.129}_{-0.164}$ at a scale of Q^2=10 GeV^2, but with sizable uncertainties. The uncertainties were determined by mapping out the χ^2 profile for the truncated integral with the robust Lagrange multiplier method. An increase of $\boldsymbol{\Delta\chi^2/\chi^2 = 2\%}$ was identified by DSSV as a faithful estimate of PDF uncertainties [3] and will be used in this document as well.

In 2009, with improved luminosity and polarization, as well as upgraded triggering and data acquisition systems at STAR, both experiments considerably improved the uncertainties in A_{LL} measurements at $\sqrt{s}=200\ \mathrm{GeV}$. The impact of these data on global QCD fits based on the DSSV framework is illustrated in Figure 1 and 2. The fit labeled DSSV+ supplements the RHIC data used in the original DSSV analysis with recent results from polarized deep-inelastic scattering obtained by COMPASS [4], and the results denoted as DSSV++ include, in addition, the 2009 RHIC data shown in Figure 1 (left). The preliminary DSSV++ fit is fully consistent with the previous DSSV uncertainty estimate and shows a preference for a sizable (relative to the total proton spin of $1/2\hbar$) gluon contribution, $\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.10^{+0.06}_{-0.07}$, with significantly reduced uncertainties. Despite this very important achievement, uncertainties for Δg(x) remain significant in the presently unmeasured small x region and prevent a reliable determination of the full integral, see Figure 2.

To further improve the Δg(x) constraint and its integral, we plan to follow three steps: (1) reduce the statistical and systematic uncertainties on the two workhorses of the RHIC Δg program, jet and π^0 A_{LL}. (2) Make use of correlation measurements such as di-jets and di-hadrons which give access to the partonic kinematics and thus the functional form of Δg(x) (Note: at LO $x_1 = p_T(e^{-\eta_1} + e^{-\eta_2})/\sqrt{s}$ and $x_2 = p_T(e^{\eta_1} + e^{\eta_2})/\sqrt{s}$). First results from di-jets and di-π^0 from STAR and PHENIX have been released, and projections for STAR di-jets are shown in Figure 3 (3) Access lower x by performing measurements at $\sqrt{s}$ =500 GeV and at large forward rapidity. Projections for π^0 A_{LL} measurements in the forward PHENIX calorimeter are shown in Figure 3. With this set of results, we will determine the gluon spin contribution to the proton spin in the x range of 0.002-0.2.

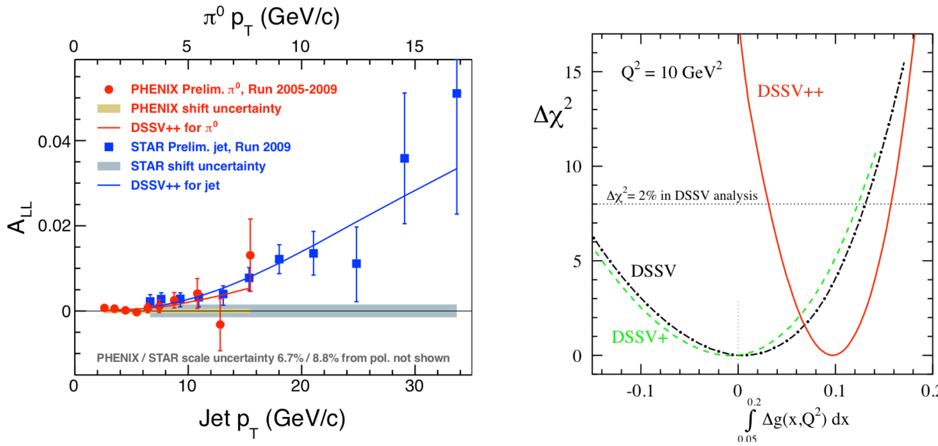

Figure 1: Recent preliminary 2009 data compared to the DSSV++ fit **(left)** and the χ^2 profile for the integrated gluon contribution in the x region currently probed at RHIC for $\sqrt{s}$ = 200 GeV **(right)**.

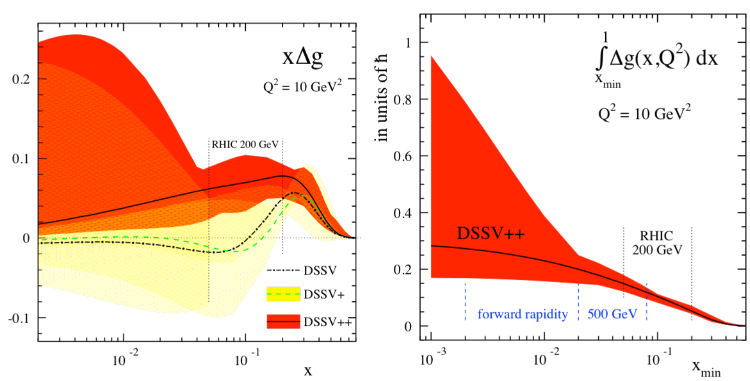

Figure 2: Uncertainties in $\Delta g(x)$ with and without RHIC 2009 data **(left)** and in the integral computed in the range from x_{min} to 1 **(right)** at a scale of 10 GeV^2.

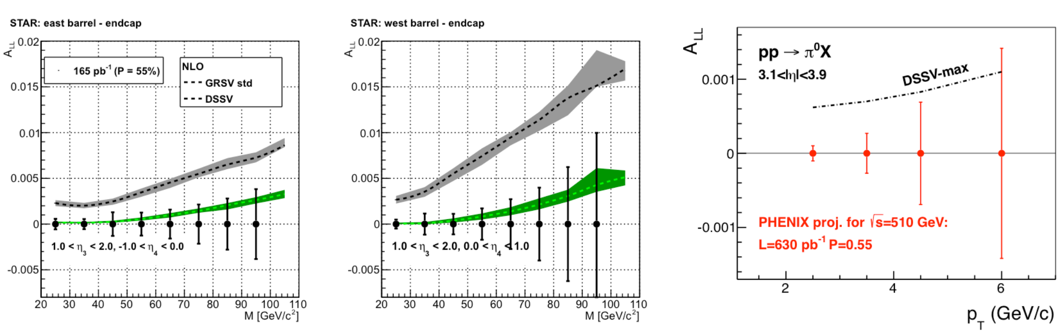

Figure 3: Projected statistical uncertainties for ALL of di-jets at mid-forward rapidity at $\sqrt{s}$ = 500 GeV as function of di-jet mass **(left, middle)** and for electromagnetic clusters in the PHENIX MPC for $3.1 < \eta < 3.9$ **(right)**. Note: the projections quote delivered luminosities.

The polarized sea quark distributions

Parity violation is a fundamental phenomenon in nature. Even though very well established and tested, its observation in polarized p+p scattering at RHIC is a qualitatively new measurement. The production of $W^{+(-)}$

bosons at $\sqrt{s}$ =510 GeV provides an ideal tool to study the spin-flavor structure of sea quarks inside the proton. The left-handed W boson only couples to (anti)quarks of a certain helicity, giving rise to large parity-violating single spin asymmetries A_L in longitudinally polarized p+p collisions at RHIC. In addition, the coupling of the W's to the weak charge correlates directly to quark flavor. Ignoring quark mixing, $W^{+(-)}$ bosons are dominantly produced through $u+\bar{d}$ ($d+\bar{u}$) interactions at tree-level and can be detected through their leptonic decays $\vec{p}+p \rightarrow W^{\pm}+X \rightarrow l^{\pm}+X$. Measurements of the transverse momentum and pseudorapidity dsitribution of the decay leptons can be compared with a recent theoretical calculation at next-to-leading order accuracy [5]. By selecting certain kinematics, the size of the expected asymmetry, and the sensitivity to the quark or antiquark helicity, can be enhanced.

The ultimate goal of the W-measurements is to explore the details behind the small total quark and anti-quark spin contribution to the proton spin measured by DIS at a much higher scale set by the large W mass, $Q^2 \sim 6400\ \mathrm{GeV}^2$ at a medium momentum fraction, $0.05 < x < 0.4$. Do anti-quarks play a decisive role in this? Do $\bar{u}$ and $\bar{d}$ carry similar polarization? This question becomes all the more interesting in view of the large difference between the spin-averaged $\bar{u}$ and $\bar{d}$ found in Drell-Yan measurements. Models of nucleon structure generally make clear predictions about the flavor asymmetry in the sea [6]. For example, since u quarks in the proton are primarily aligned with the proton spin while d quarks carry opposite polarization, one finds from considerations based on the Pauli principle the qualitative expectations $\bar{u} \geq 0$ and $\bar{d} \leq 0$ [6], and there are arguments that the flavor asymmetry in the nucleon should be even larger in the polarized than in the spin-averaged case, $\left|\Delta\bar{u}-\Delta\bar{d}\right| > \left|\bar{u}-\bar{d}\right|$.

The polarized semi-inclusive DIS measurements are sensitive to the quark and antiquark spin contributions separated by flavor [3]. Dedicated measurements of the quark and anti-quark polarizations have been performed in polarized semi-inclusive DIS by tagging definite hadrons in the final state. Data have been obtained by the SMC, HERMES, and COMPASS collaborations at scales of $Q^2 \sim 1 - 50\ \mathrm{GeV}^2$ [4,7]. These data are included in the global analysis, labeled DSSV+ shown in Figure 1 (right) and Figure 5, and indeed the results give first measurements of the polarized light sea quark parton distributions. This analysis relies on a quantitative understanding of the fragmentation of quarks and antiquarks into observable final-state hadrons, an assumption the analysis of the $W^{\pm}$ data is entirely free of. While the sum of the contributions from quark and antiquark parton distribution functions (PDFs) of the same flavor is well constrained in this fit, the uncertainties in the polarized antiquark PDFs separated by flavor remain relatively large.

The STAR preliminary results on $A_L^{W^{\pm}}$ taken during 2012 shown in Figure 4 (left) have been included in the DSSV pQCD-fit. Figure 5 shows the results for the χ^2 profile for the truncated integral for $\Delta\bar{u}$ and $\Delta\bar{d}$ in the range $0.05 < x < 1$ at Q^2=10 GeV^2. A clear improvement on the determination of the polarisation of the light sea quarks is observed. For $\Delta\bar{u}$ a shift away from the current best mean value is observed. This is explained by $A_L^{W^-}$ lying above the central curve based on DSSV+. Already, with only the preliminary 2012 STAR data, the new global analysis shows a preference for $\Delta\bar{u} > \Delta\bar{d}$ in the range x > 0.05. The same fit has been repeated based on the expected uncertainties for $A_L^{W^{\pm}}$ after the 2013-run for both STAR and PHENIX, as shown in Figure 4 (right). A clear further improvement in the truncated integral is observed (solid blue line). The lower panels in Figure 5 show for this fit also the improvement on the polarized light sea quark parton distributions as function of x.

In summary these results show clearly that the RHIC W program will lead to a substantial improvement in the understanding of the light sea quark polarizations in the nucleon with the expected statistics of the next run.

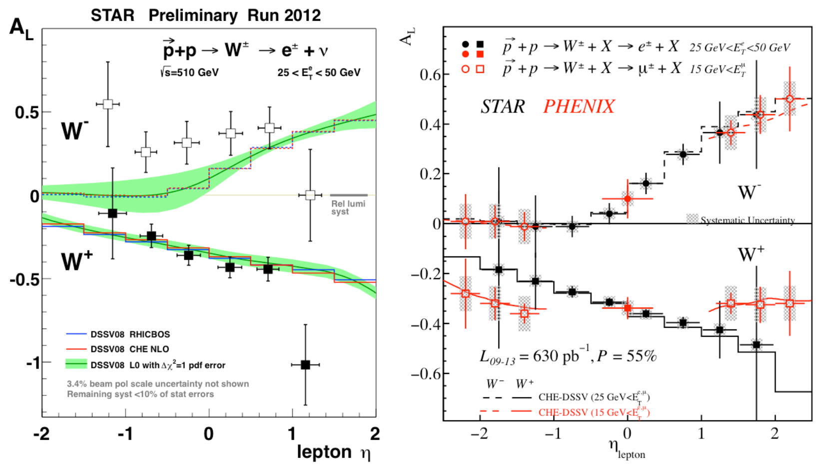

Figure 4: A_L for $W^{\pm}$ as measured by STAR in 2012 **(left)**. Expected uncertainties for A_L for $W^{\pm}$ for PHENIX and STAR after the 2013 run. The asymmetries have been randomized around the central value of DSSV to obtain the results from the pQCD-fit shown in Fig 5. **(right)**. Note: the projections quote delivered luminosities.

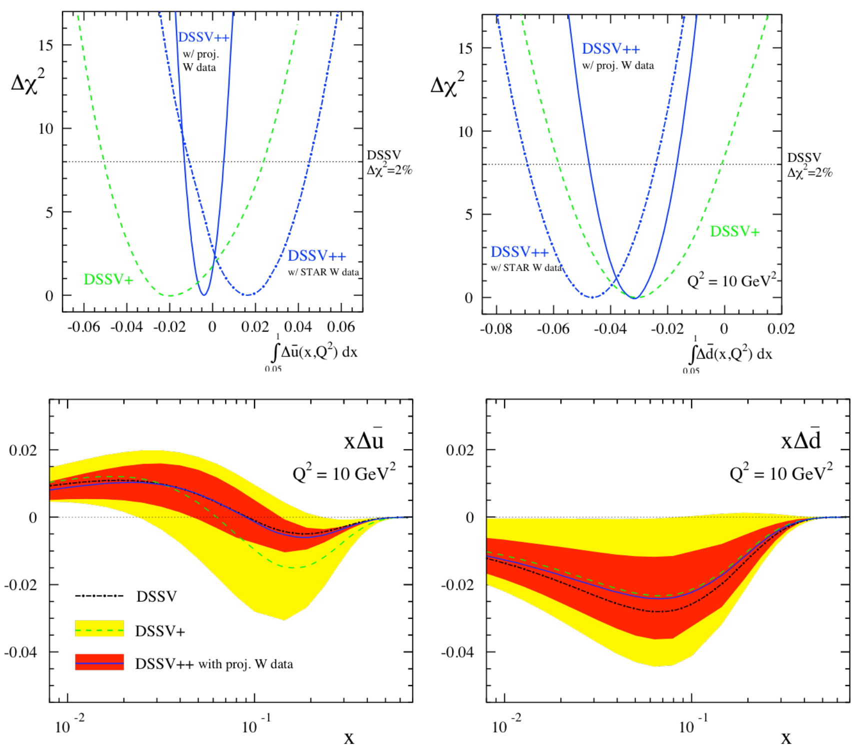

Figure 5: χ^2 profiles and x-dependent uncertainty estimates for $\Delta\bar{u}$ **(left)** and $\Delta\bar{d}$ **(right)** with (DSSV++) and without (DSSV, DSSV+) including the projections for W boson A_L data shown in Fig. 4. In the χ^2 profiles we also illustrate the impact of the preliminary 2012 STAR data.

Transverse spin structure of the proton

Transverse single spin asymmetries (SSA) in hadronic processes have a more than 30 year history and recently have attracted renewed interest, both experimentally and theoretically. First measurements at RHIC have extended the observations from the fixed-target energy range to the collider regime. Experimental studies in DIS show remarkably large SSAs in semi-inclusive hadron production. On the theoretical side, various mechanisms have been proposed to generate sizable SSAs in the QCD framework: transverse momentum dependent parton distributions, fragmentation functions, and the collinear quark-gluon-quark correlation Qiu-Sterman mechanism. Future experiments at RHIC will provide opportunities to study these mechanisms in detail and advance our understanding of the nucleon structure and QCD dynamics.

Transverse asymmetries at RHIC

Single spin asymmetries in inclusive hadron production in proton-proton collisions have been measured at RHIC for the highest center-of-mass energies to date, $\sqrt{s} = 500$ GeV. The large SSAs observed in these processes impose great challenges in theoretical understanding of spin phenomena in hadron physics. Figure 6 summarizes the measured asymmetries from different experiments as function of Feynman-x and transverse momentum.

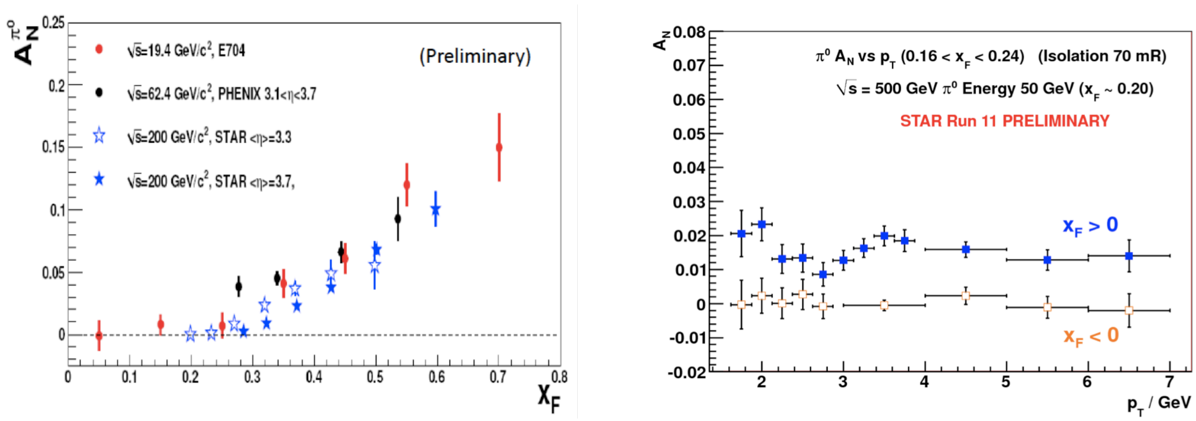

Figure 6: Transverse single spin asymmetry measurements at different center-of-mass energies as function of Feynman-x **(left)** and p_T-dependence at $\sqrt{s} = \mathbf{500\ GeV}$ **(right)**.

For a sufficiently large-scale p_T, collinear factorization is considered an appropriate approach to calculate the spin asymmetries. Indeed, next-to-leading collinear factorization calculations predict very well the spin-averaged cross sections for $\sqrt{s} \geq 200$ GeV. Since the leading partonic scattering does not generate single spin asymmetries, we have to go beyond the naïve parton model by using collinear quark-gluon-quark correlations, which have been systematically studied in the last few years. At the same time, a transverse momentum dependent model has been applied to the SSAs in these hadronic processes as well. Here, various underlying mechanisms can contribute and need to be disentangled to understand the experimental observations in detail, in particular the p_T-dependence. These mechanisms are associated with the spin of the initial state nucleon (Sivers or Qiu-Sterman effects) and outgoing hadrons (Collins effects). We identify observables below, which will help to separate the contributions from initial and final states, and will give insight to the transverse spin structure of hadrons.

Future Opportunities

The hard processes at RHIC open unique possibilities to explore transverse spin structure of the nucleon as well as transverse momentum dependent (TMD) parton distribution and fragmentation functions. The TMD parton distributions are extensions of the usual Feynman parton distributions and allow us to study the three-dimensional picture of partons inside the nucleon. They are also closely related to the generalized parton distributions and orbital angular momenta. At RHIC we can study evolution and universality properties of these functions in addition to mapping them out in a phase space not previously accessible. Polarized nucleon-nucleus collisions may provide further information about the origin of SSA in the forward direction and the saturation phenomena in large nuclei at small x.

Sivers effect

The Sivers function $f_{1T}^{\perp}$ describes the correlation of transverse momentum with the transverse spin of the nucleon. A non-vanishing $f_{1T}^{\perp}$ means that the parton distribution will be azimuthally asymmetric in the transverse momentum space depending on the nucleon spin direction. There is evidence of a quark Sivers effect in semi-inclusive DIS (SIDIS) measurements of the HERMES, COMPASS, and JLab Hall-A experiments [8]. An important aspect of the Sivers effect, which has emerged from theory lately, is its process dependence and the color gauge invariance.

In SIDIS, the quark Sivers function arises as a final state effect from the exchange of (infinitely many) gluons between the struck quark and the remnants of the target. On the other hand, for the virtual photon production in the Drell-Yan process, the Sivers asymmetry appears as an initial state interaction effect. As a consequence, the quark Sivers functions are of opposite sign in these two processes and this non-universality is a fundamental prediction from the gauge invariance of QCD. The experimental test of this sign change is one of the open questions in hadronic physics, which RHIC will be able to help answer. In addition, the wide Q^2 range at RHIC as compared to existing world data from DIS experiments will provide the much-needed input to study the energy and scale dependence for these transverse momentum dependent observables, which is currently under intense theoretical discussion.

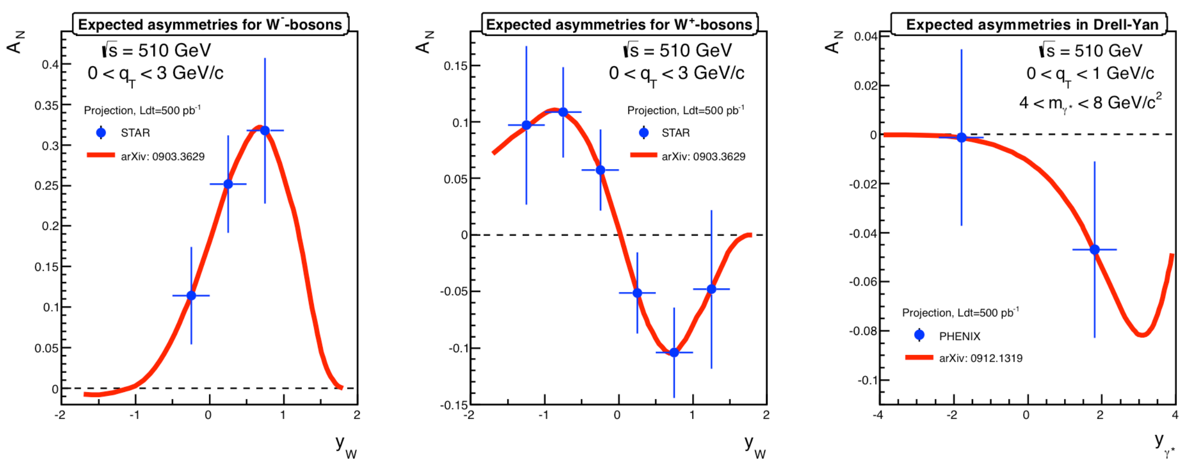

Figure 7: Expected uncertainties for transverse asymmetries in $W^{\pm}$ **(left, middle)** and Drell-Yan production **(right)** from PHENIX and STAR compared to theoretical predictions based on the SIDIS measurements. These asymmetries provide an essential test for the fundamental QCD prediction of a sign change of the Sivers function in hadronic collisions with respect to SIDIS. Note: the projections quote delivered luminosities.

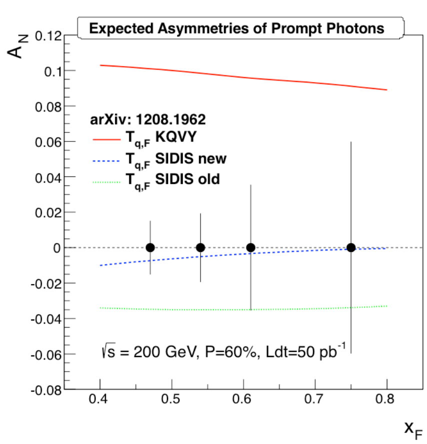

Figure 8: Projected errors for prompt photon SSA in the PHENIX MPC-EX. The error bars are combined statistical and systematic errors, including the subtraction of the π^0 and η background contributions to the inclusive asymmetry. The curves shown are predictions in the collinear quark-gluon-quark correlation approach based on SIDIS data (green, blue) and p+p data (red). This measurement will be essential in determining the process contributions to transverse SSA, especially the Sivers function at large x. Note: the projections quote delivered luminosities.

While the required luminosities for a meaningful measurement of asymmetries in Drell-Yan production are challenging, see Figure 7, other channels can be exploited in p+p collisions, which are similarly sensitive to the predicted sign change. These include prompt photons, $W^{+/-}$ and Z bosons, heavy flavor, and inclusive jets and they are accessible with the existing detectors or moderate upgrades already.

Predictions for asymmetries of W/Z bosons are significant in the RHIC kinematic region with a pronounced rapidity dependence [9]. These measurements at very large Q^2 would also provide essential input for the evolution effects of the Sivers function as mentioned above.

Transverse single spin asymmetries have been measured at RHIC for π^0 and inclusive jets previously [10] at mid-rapidity. Although these are consistent with zero, model calculations [11] indicate they impose significant constraints on the contributions from the gluon Sivers function (or the three-gluon correlation). Additional data was taken at $\sqrt{s}$ = 200 GeV and 500 GeV during the latest RHIC runs and will allow more precise determination of inclusive jet asymmetries.

The forward direction of the polarized nucleon has played very important role to observe the large SSAs, which makes this kinematic region essential in the separation of underlying effects. Currently STAR has nearly full coverage with electromagnetic calorimeters from $-1<\eta<4$ and the reconstruction of jets in the regions without charged track information is being investigated. STAR is also investing in an upgrade to the inner sectors of the existing Time Projection Chamber. This will increase the tracking coverage, and therefore charged particle and traditional jet reconstruction, to $-1<\eta<2$. PHENIX is in the process of upgrading the forward calorimeters (MPC-EX upgrade) with a preshower detector that will allow the identification of direct photons (see Figure 8) and neutral pions up to energies of 80 GeV at $3.0<\eta<3.8$.

Transversity and Collins effect

The Collins function $H_1^\perp$ describes a correlation of the transverse spin of a scattered quark and the transverse momenta of the fragmentation products and as such can lead to an asymmetry of the distribution of hadrons in jets. Contrary to the Sivers effect discussed above, the Collins fragmentation function is universal among different processes: SIDIS, e^+e^- annihilation, and p+p collisions. This is of special importance to the p+p case where it is always coupled to the chirally odd quark transversity distribution. The integral of transversity over *x*, when compared to the tensor charge from lattice QCD calculations, provides a fundamental test of the theory of QCD itself.

Non-vanishing Collins effects have been observed in SIDIS and e^+e^- annihilation [12] and STAR has recently measured Collins asymmetries of charged pions in jets, which show the feasibility of the method. The results so far are based on 2.2 pb^{-1} and are dominated by the systematic uncertainties.

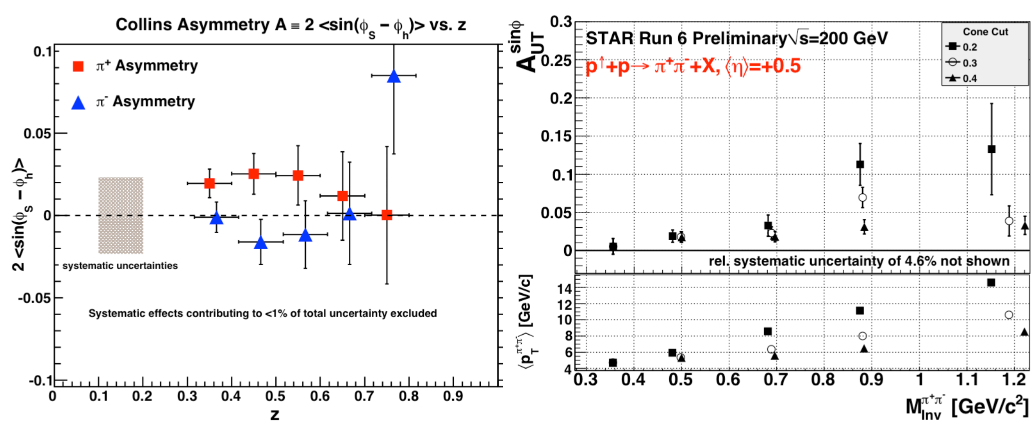

Figure 9: Collins asymmetries in hadron distributions with respect to the jet axis **(left)** and interference fragmentation function asymmetries of di-pions **(right)** as measured by STAR in 2006 at $\sqrt{s}$ = 200 GeV.

The two-hadron interference fragmentation functions (IFF) have been measured in e+e- annihilation and, in combination with the quark transversity distribution, in deep-inelastic scattering [13]. This provides a model independent way to access the quark transversity distribution when the existing data will be compared with similar measurements from RHIC. The preliminary RHIC results show that non-zero asymmetries arise at forward rapidities of the hadron pair especially at increased transverse momenta. The Collins and IFF analyses are being pursued at both $\sqrt{s}$ = 200 GeV (2012) and 500 GeV (2011) leading to a reduction of the statistical errors in Figure 9 by a factor of three. Improved analysis techniques are expected to also reduce the systematic uncertainties in the Collins asymmetries by an order of magnitude. With moderate upgrades the phase space can be extended into regions that are currently not reached in SIDIS, in particular the high-x region of transversity. This will provide a unique test of the universality of the quark transversity distribution and valuable input for the evolution of TMD fragmentation functions utilizing the above-mentioned Collins asymmetries.

The longer term RHIC SPIN Program

Both collaborations plan in the 2^{nd} half of the decade detector upgrades to considerably expand their capabilities to answer the physics questions discussed above. The upgrades are motivated by spin physics goals of extending the gluon polarization measurements towards smaller gluon fractional momentum values through forward correlation measurements and the study of transverse spin phenomena through precision measurements of SSAs in polarized DY, direct photon production, inclusive jets as well as the above described Collins and IFF asymmetries. The cold nuclear matter and heavy-ion physics goals to be answered by these upgrades are described elsewhere.

Having a polarized He-3 beam available in RHIC and tagging the struck quark flavor through the produced hadron species, will allow for a full quark flavor separation of transverse momentum dependent parton distributions (i.e., transversity and Sivers function). Because of the anti-aligned spins of its two protons, He-3 basically constitutes a polarized neutron (d-quark) beam. Having the additional capability to tag the neutron scattering events by measuring the spectator protons in “Roman Pots” will make the measurement extremely clean. Details on the physics capabilities and all aspects how to realize a polarized He-3 beam in RHIC have been discussed during a workshop in September 2011 and are available here [14].

The forward sPHENIX upgrade

The PHENIX Collaboration is in the process of designing a series of upgrades to considerably expand the physics capabilities [15] and make full use of the constantly increasing luminosity at RHIC. The central-rapidity spectrometer will consist of a 2 T solenoid of radius 70 cm surrounded by an electromagnetic calorimeter (EMCal) and a hadronic calorimeter with uniform coverage for $|\eta|<1.1$ to carry out measurements focusing on jets and electromagnetic probes. The addition of charged particle tracking beyond the existing PHENIX silicon vertex detector and a preshower with fine segmentation in front of the electromagnetic calorimeter will allow to do precision measurements of hadrons (including π^0s up to p_T= 40 GeV/c) and electrons (di-leptons and from heavy flavor decays). The open geometry of the magnetic solenoid also allows for the addition of a forward angle spectrometer aimed at measuring photon, hadron, jet and electron observables.

Precision Drell-Yan measurements in the forward spectrometer via di-electrons will require an EMCal, charged particle tracking and heavy flavor tagging for background rejection. The addition of a hadronic calorimeter is highly desirable for jet reconstruction, which will greatly extend PHENIX’s ability to measure Sivers, Collins and IFF asymmetries at forward rapidities. Particle tracking will serve to study the dependencies on the fractional momentum of a hadron or a hadron pair in the jet. Particle identification is important for a flavor decomposition of the transverse spin effects.

A "strawman" design of the forward spectrometer in Figure 10 is being used for sensitivity studies and to establish detector requirements to address the physics goals outlined.

The envisioned spectrometer acceptance covers 1.2 to 4 in pseudorapidity. An extension or modification of the central solenoid is needed to provide a sufficiently strong tracking field in the forward spectrometer, however in the very forward region, $3<\eta<4$, an additional magnetic field would be needed to retain the momentum resolution. The current PHENIX EMCal and MPC are planned to be re-configured for re-use in the upgraded forward spectrometer.

Provided the approval of this upgrade project by funding agencies, the construction of new detector systems is scheduled to start in 2015 and the installation and recommissioning of the basic elements of spectrometers is planned for the year of 2019.

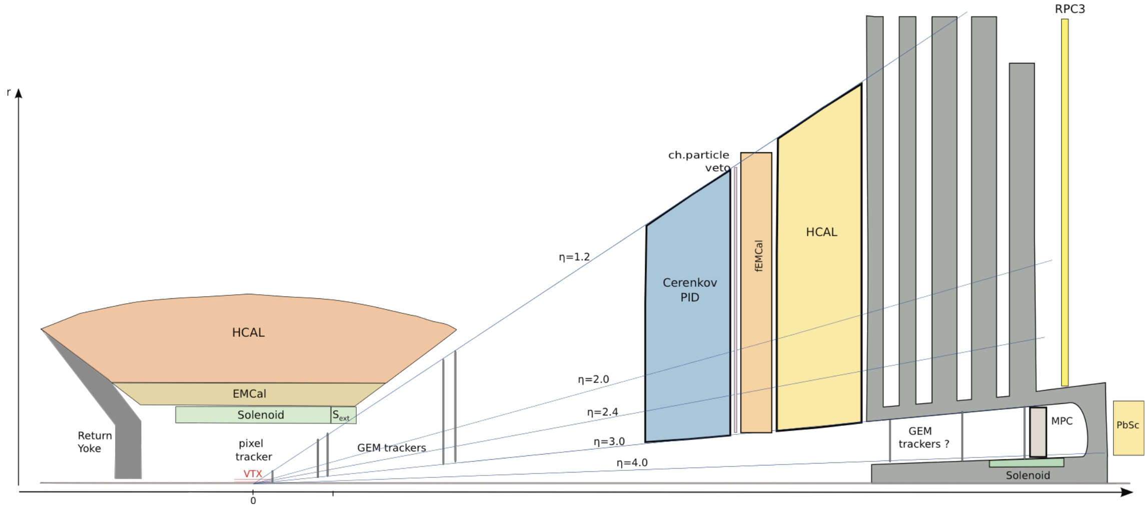

Figure 10: Schematic sketch of the sPHENIX central and forward spectrometer layout.

The forward STAR upgrade

The STAR collaboration envisions new instrument upgrades [17] in the second half of the decade to extend the capabilities for measuring jets, electrons, photons, and leading particles, in particular at forward rapidity.

At central rapidities an upgrade is envisioned to the existing Time-Projection Chamber. A key aspect is an increase by a factor two or more of the number of instrumented pad rows for the inner sectors, which will extend the tracking and particle identification capabilities by about half a unit in rapidity. This will serve many areas of the STAR physics program, including in particular the ability to measure the Collins spin asymmetries in the distribution of hadrons within jets and in two-hadron production over an extended kinematic range.

The forward detector upgrade concept includes tracking detectors for charged particles, electromagnetic and hadronic calorimeters, as well as a forward particle identification detector. `Figure 11` shows the schematic design that is being used to quantify detector requirements and measurement sensitivities. A staged approach is envisioned, with the first stage consisting in the Forward Calorimeter System (FCS). The second stage of this ugpgrade aims at particle separation capability for baryons and mesons. Either threshold Cherenkov or RICH detector technologies are being considered. GEM-based detectors are currently envisioned to provide charged particle tracking.

The FCS is anticipated to be a compensated calorimeter for electron and hadron responses consisting of a front Electromagnetic Calorimeter (EMCal) followed by hadronic calorimeters. The EMCal is expected to adopt a new calorimeter construction technology, using Tungsten-Powder and scintillating fibers. This technology is being developed also as part of an ongoing R&D program aimed at a future Electron-Ion Collider and compact modules with excellent energy resolutions and detector uniformity have been built and tested with beams. The E864 Spaghetti Calorimeter modules will be re-used to provide hadronic calorimetry for part of the forward acceptance.

They will be complemented at more forward rapidities with new modules made of lead and scintillator plates. The FCS will thus provide measurement capability for forward jet production and initial Monte Carlo simulations indicate a suitable discrimination of electrons and hadrons, as necessary for example for a Drell-Yan physics program.

The aimed for schedule is such that the construction of the FCS will start in 2015 followed by installation and commissioning in 2017.

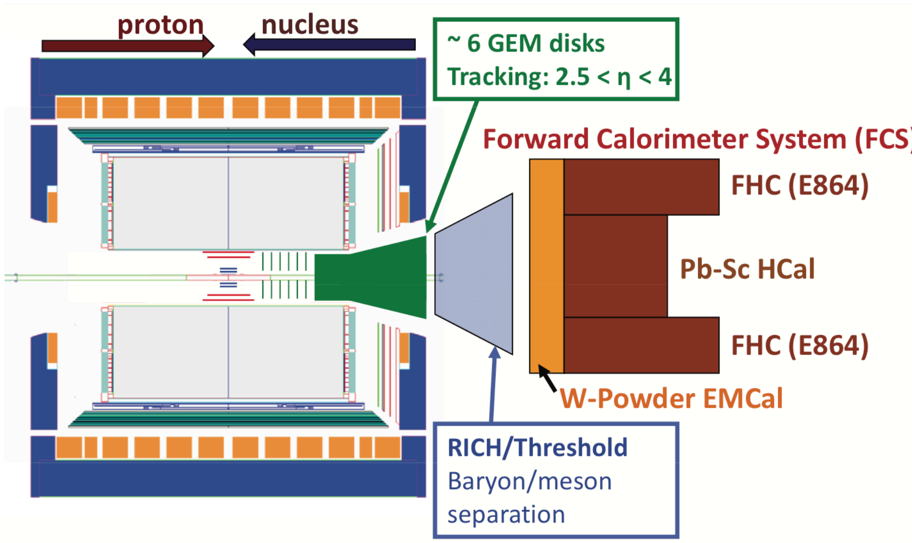

Figure 11: Schematic sketch of the STAR forward spectrometer upgrade.

Polarised Proton-Nucleus Collisions

Single Transverse Spin Asymmetry in Polarized Proton--Nucleus Collisions

The scattering of a polarized proton on an unpolarized nuclear target is an exciting new idea, which appears to have the potential to extend and deepen our understanding of QCD. In the frame where the nucleus is relativistic, its wave function consists of densely packed quarks and gluons, which constantly split and merge with each other. At high enough energies the density of the gluons is so high that the *saturation* regime is reached, characterized by strong gluon fields and scattering cross sections close to the unitarity bound. The saturated wave function is often referred to as the Color Glass Condensate (CGC) and is reviewed in detail in [17-21].

Scattering a polarized probe on this saturated nuclear wave function may provide a unique way of probing the gluon and quark transverse momentum distributions (TMDs). In particular, the single transverse spin asymmetry A_N may provide access to the elusive nuclear Weizsaecker-Williams (WW) gluon distribution function [22,23], which is a solid prediction of the CGC formalism [24-26] but is very difficult to measure experimentally. The nuclear effects on A_N may shed important light on the strong interaction dynamics in nuclear collisions while the theoretical approaches based on CGC physics predict that hadronic A_N should decrease with increasing size of the nuclear target [27-31], some approaches based on perturbative QCD factorization predict that A_N would stay approximately the same for all nuclear targets [32]. The asymmetry A_N for prompt photons is also an important to measure. The contribution to the photon A_N from the Sivers effect [33] is expected to be non-zero, while the contributions of the Collins effect [34] and of the CGC-specific odderon mediated contributions [31] to the photon A_N are expected to be suppressed [31,35]. Clearly experimental data on polarized proton-nucleus collisions is desperately needed in order to distinguish different mechanisms for generating the single spin asymmetry A_N in nuclear and hadronic collisions.

Access to the Generalized Parton Distribution E_g

"How are the quarks and gluons, and their spins distributed in space and momentum inside the nucleon? What is the role of orbital motion of sea quarks and gluons in building the nucleon spin?" are key questions, which need to be answered to understand overall nucleon properties like the spin structure of the proton. The formalism of generalized parton distributions (GPDs) provide till today the only theoretical framework, which allows to provide some answers to the above questions [36]. The experimentally best way to constrain GPDs is through exclusive reactions in DIS, i.e., deeply virtual Compton scattering. RHIC with its possibility to collide transversely polarized protons with heavy nuclei has world-wide the unique opportunity to measure A_N for exclusive J/Ψ production in ultra-peripheral p↑Au collisions (UPC) [37]. A non-zero asymmetry would be the first signature of a non-zero GPD E for gluons, which is sensitive to spin-orbit correlations and intimately connected with the orbital–angular momentum carried by partons in the nucleon and thus with the proton spin puzzle. To measure A_N for exclusive J/Ψ production in ultra-peripheral p↑Au collisions provides an advantage in rate as the emission of the virtual photon from the Gold nucleus is enhanced by Z^2 compared to ultra-peripheral p↑p collisions. Exclusivity of the process can be ensured detecting the scattered polarized proton in "Roman Pots" and vetoing the break-up of the gold nucleus.

Summary

The physics program described in this document can in its whole only be accomplished over multiple years, as it requires different running conditions:

- transverse or longitudinal beam polarization,
- collision of different beam species p+p or p+A,
- different center-of-mass energies.

The table summarizes a possible running plan taking into account when new machine or detector systems are available that will be needed to perform certain measurements. Only measurements related to the RHIC spin program are listed. It is noted that pA collisions not only address important questions in spin physics, but even more importantly give the unique opportunity to study cold QCD matter effects as gluon saturation.

Years	Beam Species and Energies	Science Goals	New Systems Commissioned/Required
2013	500 GeV $\vec{p}+\vec{p}$	Sea antiquark and gluon polarization	Electron lenses upgraded pol'd source
2014	200 GeV $p^{\uparrow}+p$ 200 GeV $\vec{p}+\vec{p}$	Unravel underlying sub-processes for A_N Improve precision on $\Delta g(x)$	PHENIX Muon Piston Calorimeter Extension
2015-2017	200 GeV $p^{\uparrow}+A$ 500 GeV $p^{\uparrow}+p$ 500 GeV $\vec{p}+\vec{p}$	Unravel underlying sub-processes for A_N, GPD E, First measurement of PHENIX: A_N(DY), STAR: A_N(W/Z) Unravel underlying sub-processes for A_N $\Delta g(x)$ at low-x, sea antiquark polarizations	STAR inner TPC pad row upgrade
>2018	200 GeV $p^{\uparrow}+A$ 500 GeV $p^{\uparrow}+p$	Unravel underlying sub-processes for A_N, GPD E Precision measurements of transversity, Sivers, IFF, and A_N(DY)	sPHENIX STAR forward physics upgrade Polarized He-3 beams

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